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PRESENTATION 4.3.3

STV ENGINE DESIGN CONSIDERATIONS

PRESENTED TO

SPACE TRANSPORTATION PROPULSION SYSTEMS SYMPOSIUM

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ENGINE DESIGN CRITERIA AND ISSUES

The engine workshop organized by MSFC resulted in agreement that the items listed were the major criteria which should be considered in developing detailed design requirements for the STV engine. Several of the items are not truly separate but are different aspects of the overall vehicle-engine system. For example, space basing requires efficient vehicle turn around operations to accomplish mission goals at reasonable cost. Similarly health monitoring tasks are affected by the system/subsystem interface architecture and provide data to define vehicle status for continuing man rating through the next mission.

STV ***ENGINE DESIGN CRITERIA AND ISSUES***

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1. MAN RATING
2. SPACE BASING
3. OPERATIONS
4. SYSTEM/SUBSYSTEM I/F ARCHITECTURE
5. HEALTH MONITORING
6. PERFORMANCE
7. MARGINS
8. ENGINE CONFIGURATION/CHARACTERISTICS

DESIGN REQUIREMENTS FOR MAN RATING

Man rating is the most basic and possibly the only firm requirement for an engine to support the human exploration initiative. The document JSC-23211 "Guidelines for Man Rating Space Systems" provided man rating guidelines intended to be applicable to all future NASA missions. The task at hand is to convert these guidelines into mission, vehicle and engine requirements.

Safe return of the crew after any two failures has been interpreted as a requirement on the total vehicle which may result in unconventional approaches to engine interfaces and fault isolation. Trade studies must be conducted in parallel with evolution of the vehicle configuration to establish the approach to be used. For example, containment of a failed turbopump could be accomplished by the engine hardware or protective barriers could be provided between adjacent engines.

***STV* DESIGN REQUIREMENTS FOR MAN RATING**

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- MAN RATING IS A SYSTEM REQUIREMENT.
 - CRITICAL SYSTEMS MUST BE TWO FAILURE TOLERANT.
 - THE PROPULSION SYSTEM MUST PROVIDE SAFE CREW RETURN TO LOW EARTH ORBIT FROM ANY PART OF THE LUNAR MISSION.
 - AN INDEPENDENT CREW ESCAPE SYSTEM TO RETURN FROM THE LUNAR SURFACE IS NOT PRACTICAL FOR EARLY MISSIONS.
- ENGINE REQUIREMENTS DERIVED FROM SYSTEM REQUIREMENT.
 - ALTERNATIVES FOR A TWO FAILURE TOLERANT SYSTEM:
 - EACH ENGINE IS TWO FAILURE TOLERANT, OR
 - REDUNDANT ENGINES
 - ENGINES MUST BE ISOLATED TO PREVENT FAILURE PROPAGATION TO OTHER ENGINES OR SUBSYSTEMS.
 - VERY HIGH RELIABILITY IS REQUIRED
 - MAJOR FACTOR IN ENGINE AND COMPONENTS DESIGN
 - ENGINES RELIABILITY REQUIREMENT WILL BE ESTABLISHED AFTER CONFIGURATION SELECTION.

TEST REQUIREMENTS FOR MAN RATING

The engine development and qualification test programs must fully demonstrate all functional and performance design requirements to accomplish planned manned missions. Special tests should be conducted to validate safety related redundancies, fault isolation and containment of fragmented components. Testing with the engine mated to a simulated vehicle propellant system is required to explore engine system dynamics and interactions. The flight test program will evaluate engine start and autogenous tank pressurization in the same low acceleration space environment as the fully operational manned missions.

***STV* TEST REQUIREMENTS FOR MAN RATING**

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- ENGINE TEST FIRINGS SIMULATE FULL MISSION FIRINGS
 - AT LEAST TWO ENGINES TESTED TO DEMONSTRATE LIFE.
 - POST TEST DISASSEMBLY AND INSPECTION
- ENDURANCE TEST TO FAILURE.
 - POST TEST INSPECTION AND ANALYSES
 - DETERMINE FAILURE SEQUENCE
 - IDENTIFY FAILURE PRECURSORS
- DESTRUCTIVE TESTING TO VERIFY FAILURE ISOLATION.
- LUNAR ENVIRONMENT SIMULATION FOR ENGINE & VEHICLE LIFE
 - MISSION FIRING SEQUENCE AT END OF TEST
- GROUND TEST FIRINGS WITH VEHICLE PROPELLANT FEED SYSTEM
- UNMANNED FLIGHT TESTS DEMONSTRATE ESSENTIAL FUNCTIONS.

DESIGN REQUIREMENTS FOR SPACE BASING

Space basing of the STV will require that the engines remain operational after up to 5 years in the space vacuum environment. The two main issues for space basing are materials compatibility and design of the engine and vehicle interfaces for minimum maintenance.

***STV* DESIGN REQUIREMENTS FOR SPACE BASING**

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- EXPOSURE TO LOW EARTH ORBIT OR LUNAR ENVIRONMENTS FOR THREE YEARS
- SPARES STORAGE AT THE SPACE STATION IN A PROTECTED ENVIRONMENT FOR FIVE YEARS
- ACCOMMODATE ENGINE REMOVAL AND REPLACEMENT AT THE SPACE STATION AND IN LUNAR ENVIRONMENT
- ELIMINATE SPECIAL FLUIDS REQUIREMENTS FOR VALVE ACTUATION, PURGE OR OTHER PURPOSES.
- MINIMIZE PRE-MISSION CHECK OUT REQUIREMENTS AND ELIMINATE ANY LOSS OF FLUIDS IF POSSIBLE.

ENGINE OPERATIONS REQUIREMENTS

Engine related maintenance and checkout operations at the space station will incur crew costs now estimated at \$123,000 per hour. The high costs emphasize the need for highly reliable systems which will require little or no maintenance over the life of the vehicle. The reliability of the functional hardware must be supported by comprehensive instrumentation to verify the status and confirm that reliability has not been degraded over the life of the vehicle. Redundant instrumentation with additional verification by cross referencing related measurements will be required to assure that health of the hardware is correctly diagnosed.



ENGINE OPERATIONS REQUIREMENTS

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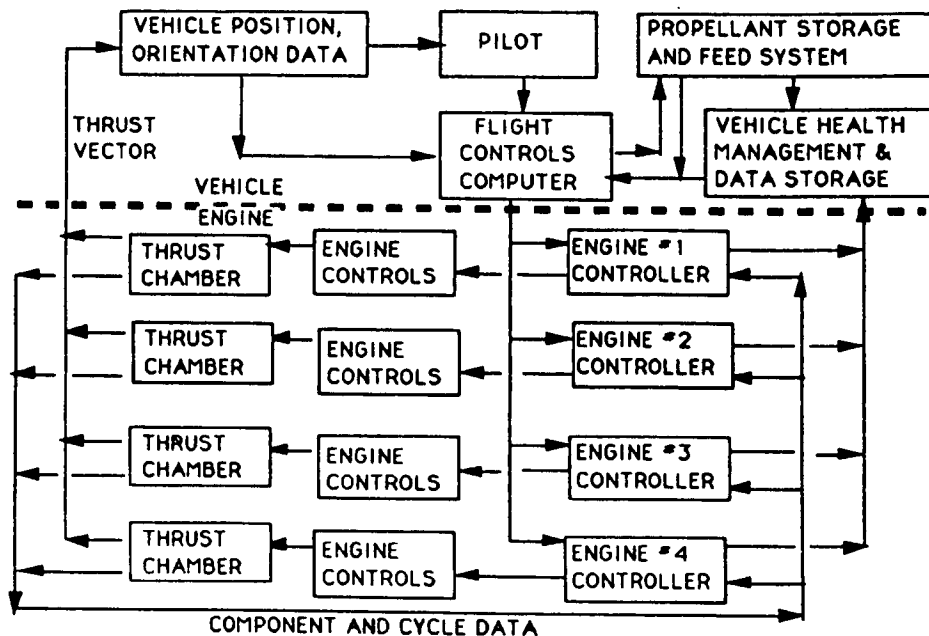
- LONG LIFE TO MINIMIZE ENGINE REPLACEMENT
- QUICK DISCONNECTS FOR FLUIDS AND ELECTRICAL INTERFACES
 - POSITIVE INDICATION OF CONNECTION
 - MAXIMUM ACCESSIBILITY
- EASILY REMOVABLE NOZZLE EXTENSION
- IMPROVED INSTRUMENTATION AND COMPUTER SYSTEM RELIABILITY
 - AUTOMATED ENGINE CHECKOUT AND INTERFACE VERIFICATION
 - INSTRUMENTATION REDUNDANCIES
- HEALTH MONITORING SYSTEM WITH CAPABILITY TO IDENTIFY FAILED COMPONENTS OR INSTRUMENTS.

HEALTH MONITORING LOGIC DIAGRAM

The propulsion system health monitoring and management functions will include the propellant system as well as the engines. It is likely that each engine will have a health monitoring capability as part of the electronic engine controller. The same data used by the engines will be evaluated and stored by the vehicle health management computer and data storage system. The vehicle system will have complete historical data records for each engine to support diagnostic functions and develop recommended engine operating strategies to satisfy vehicle propulsion requirements. Vehicle health management system recommendations will be provided to the flight controls computer where they may be overridden by the pilot if necessary during critical maneuvers.

STV HEALTH MONITORING LOGIC DIAGRAM

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HEALTH MONITORING DATA REQUIRED

The parameters identified are general propulsion system data which are applicable to the type engines and vehicle systems expected for the STV. The health management system will use vehicle propellant system data and thrust commands as well as the engines components data to evaluate the engines status and ability to continue to function.

***STV* HEALTH MONITORING DATA REQUIRED**

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- DATA PROVIDED BY THE VEHICLE
 - PROPELLANTS
 - QUANTITIES REMAINING
 - INTERFACE PRESSURES
 - INTERFACE TEMPERATURES
 - COMMANDS
 - THRUST
 - MIXTURE RATIO
 - ENGINES HISTORICAL RECORD CHARACTERIZATION
- DATA PROVIDED BY THE ENGINE
 - COMPONENTS
 - VIBRATION
 - ROTATIONAL SPEED
 - TEMPERATURES
 - STATUS (VALVES OPEN/CLOSED)
 - THERMODYNAMIC CYCLE
 - MIXTURE RATIO
 - FLOW RATES
 - PRESSURES
 - TEMPERATURES
- DATA PROCESSING AND CYCLE ANALYSES IDENTIFY POTENTIAL COMPONENT MALFUNCTION

LTV PROPELLANT FEED SYSTEM

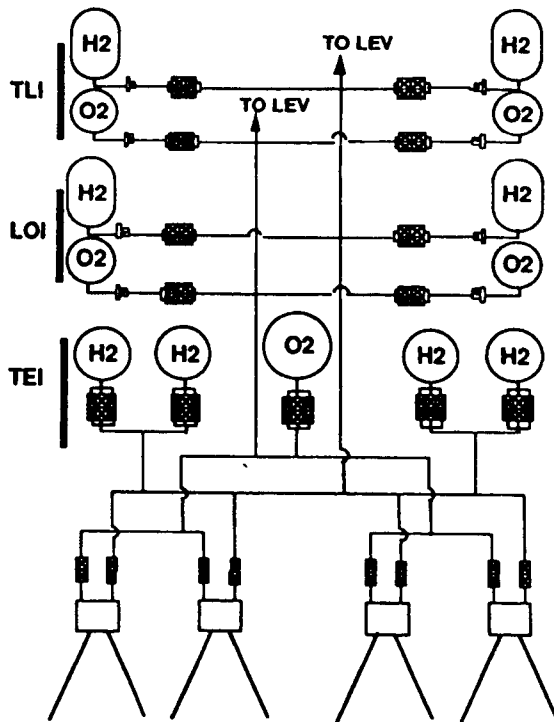
The feed system schematic of the lunar transfer vehicle (LTV) is single failure tolerant for the trans lunar injection (TLI) and lunar orbit insertion (LOI) burns. The trans earth injection (TEI) portion of the feed system is two failure tolerant to assure safe return of the crew if emergency conditions develop in lunar orbit.

Six valves at the exit of each TEI tank are arranged to provide three parallel paths for opening after any two failures. Two valves in series in each path at the tank exits provides assurance that each tank can be isolated from the system manifold after a single valve failure. The two valves in series on each propellant feed line to the engine are in series with the engine shut off valves to prevent loss of propellants with any two failures including engine failure.

STV

LTV PROPELLANT FEED SYSTEM

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•TLI AND LOI PROPELLANT SYSTEM

•QUAD REDUNDANT VALVES FOR TLI AND LOI BURNS SATISFY SINGLE FAILURE TOLERANT REQUIREMENTS TO PERFORM MISSION.

•TWO FAILURE TOLERANT SYSTEM IS NOT REQUIRED FOR TLI AND LOI BECAUSE TEI SYSTEM PROVIDES SAFE RETURN.

•TEI PROPELLANT SYSTEM

•SAFE RETURN OF THE CREW FOR MAN RATING REQUIRES A TWO FAILURE TOLERANT SYSTEM.

•PROPELLANT TANKS CONNECT TO DISTRIBUTION MANIFOLDS THROUGH PARALLEL AND SERIES TRIPLE REDUNDANT VALVE MODULES.

•TWO VALVES IN SERIES CONNECT MANIFOLDS TO ENGINES FOR TWO FAILURE TOLERANCE IN SERIES. FOUR ENGINES SATISFY PARALLEL REDUNDANCY REQUIREMENTS.

•TOTAL 78 FEED SYSTEM VALVES

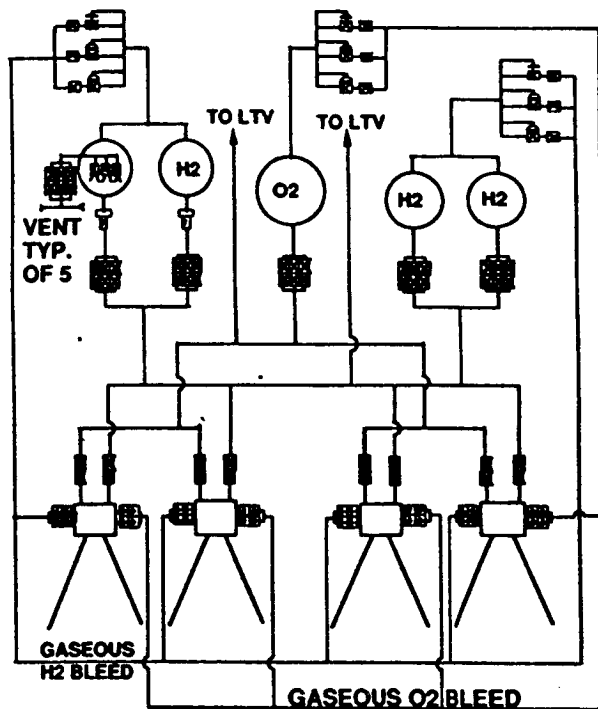
LEV PROPELLANT SYSTEM

The lunar excursion vehicle (LEV) propellant system is two failure tolerant to any catastrophic loss of fluid failure. Quad check valve arrangements for each engine autogenous pressurization line prevent loss of pressurization flow in the event of an engine failure. Hydrogen tank pairs are pressurized from a common manifold to limit the number of regulators required.

STV

LEV PROPELLANT SYSTEM

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- FEED SYSTEM
 - 46 CRYOGENIC SHUT OFF VALVES
- VENT SYSTEM
 - 15 CRYOGENIC SHUT OFF VALVES
 - 30 GAS SHUT OFF VALVES
- PRESSURIZATION SYSTEM
 - 32 CHECK VALVES
 - 9 GAS SHUT OFF VALVES
 - 9 PRESSURE REGULATORS

FEED SYSTEM FAILURE RATES

The large number of shut off valves used in the feed systems to satisfy a two failure tolerant requirement for man rating increases the probability that some valve failures will occur requiring replacement. Inlet valves of the RL10 engine were assumed to be representative of the type shut off valve applicable to the propellant feed system. Valve failure rates were estimated at 236 failures per million cycles at 50% confidence level based on 1470 RL10 firings with no failures of the two inlet valves. This failure rate results in a 50% probability of at least one valve failure after less than 25 valve cycles for the total LTV & LEV vehicle set.

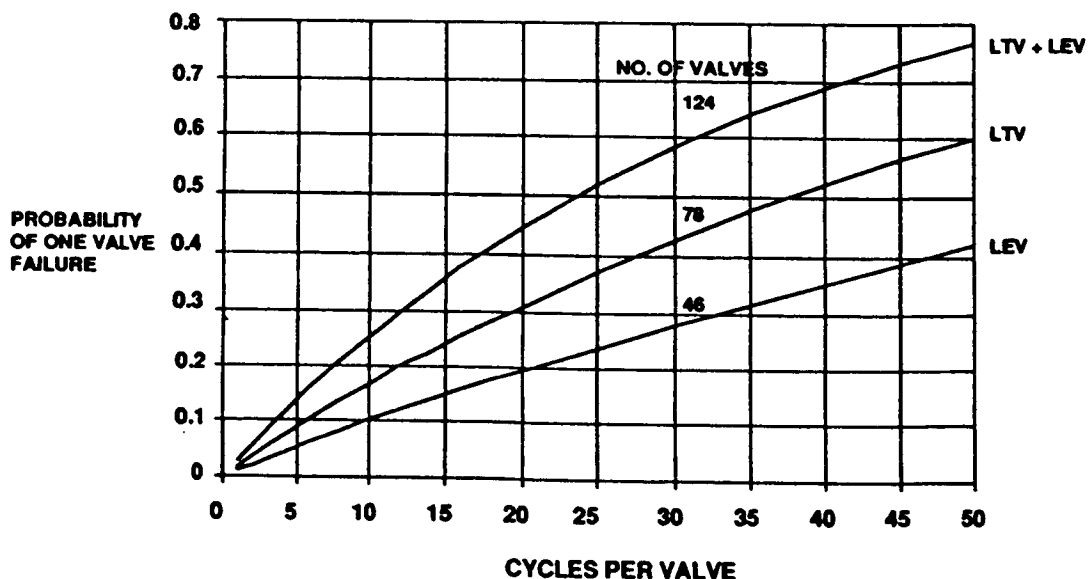
The probability of valve failures occurring in less than the desired life of the vehicle establishes a need to develop proven valve reliability data and efficient techniques for valve replacement.

STV

FEED SYSTEMS FAILURE RATES

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- VALVE RELIABILITY BASED ON RL10 INLET VALVES
- TOTAL 1470 FIRINGS WITH NO FAILURES THROUGH MAY, 1988
- COMBINED FUEL AND OXIDIZER VALVES DUE TO SIMILAR DESIGN



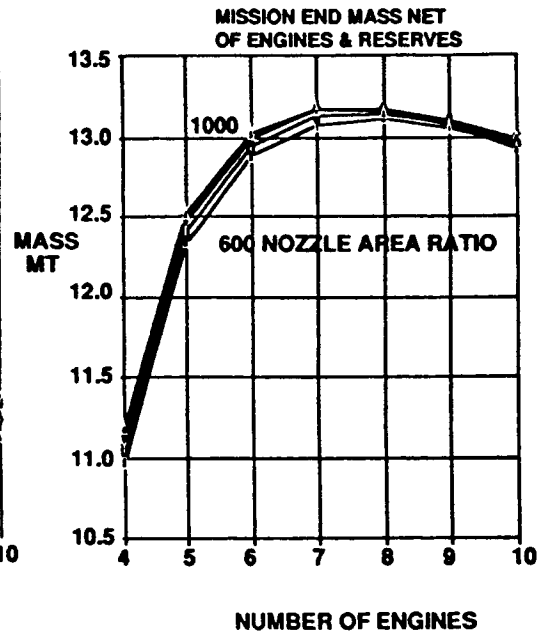
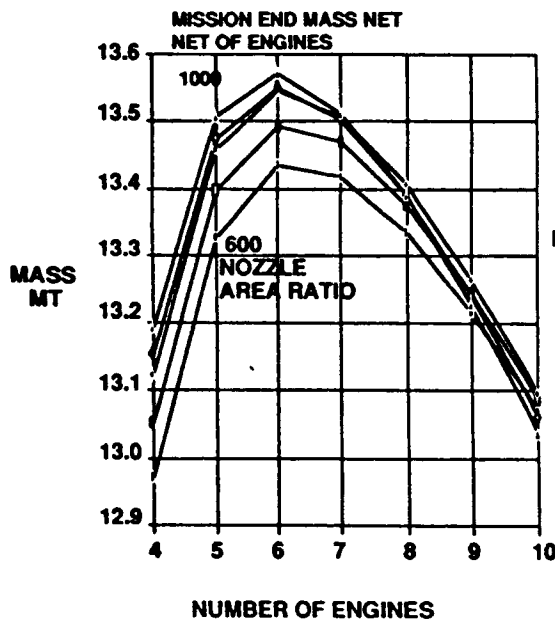
ENGINE NOZZLE TRADE FOR 98% IDEAL ISP

The equilibrium ISP trend caused the mission burnout mass net of engines and reserves to be higher for a nozzle area ratio of 1000 instead of the 600 found for the Boeing ISP trend. The burnout mass advantage of the nozzle area ratio of 1000 is small and does not appear to justify the increased engine diameter and length required.

STV ENGINE NOZZLE TRADE FOR 98% IDEAL ISP

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- ENGINE THRUST, 66723 N (15,000 LBF)
- INSTALLATION WEIGHT PENALTY 30%
- INITIAL MASS IN LEO 170,000 KG
- BOEING ENGINE PERFORMANCE & WEIGHT



AREA RATIO GIMBAL ANGLE LIMITS

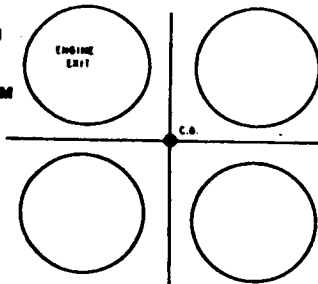
The lunar excursion vehicle engines nozzle area ratio will establish the separation required between the engines and the vehicle center line to avoid interference between the engines. A minimum separation of 15 cm between the nozzles was assumed with the engine center lines parallel to the vehicle center line to establish gimbaling angle and nozzle area relationships. If the engines thrust is pointed through the vehicle center of gravity with the 600 nozzle area ratio the maximum gimbaling angle of 20 degrees will be required when the center of gravity is nearest the gimbaling plane. The cosine thrust losses caused by pointing thrust through the C. G. for the entire thrust time would reduce the delivered specific impulse for the total thrust vector.

STV

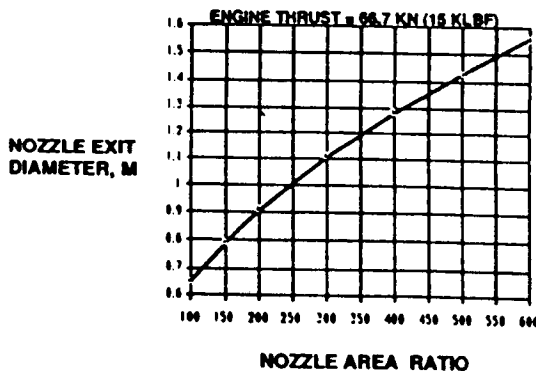
AREA RATIO GIMBAL ANGLE LIMITS

MSFC- **BOEING**

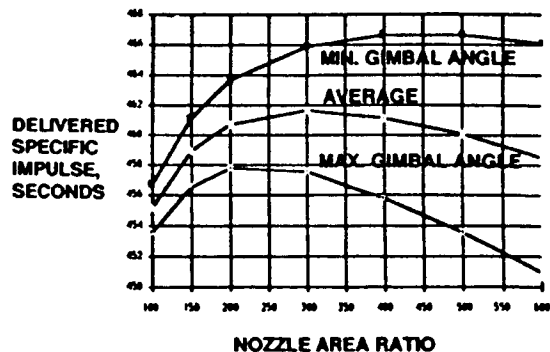
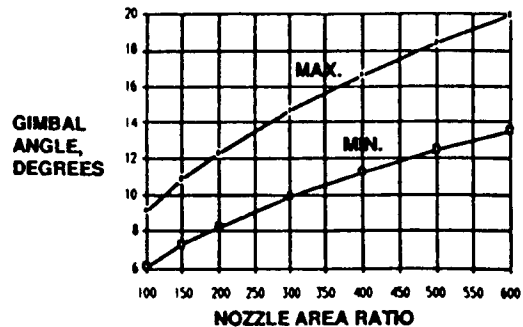
DISTANCE FROM
GIMBAL PLANE
TO C. G. VARIES
FROM 3.2 TO 4.8 M



ENGINE ARRANGEMENT



GIMBAL ANGLE TO THRUST THROUGH C.G.



REACTION CONTROL SYSTEM

An oxygen hydrogen reaction control system (RCS) has the logistic advantage of commonality with the main propulsion propellants. Development of an oxygen hydrogen thruster of the size needed for the STV would be required to realize the potential advantages. Obtaining full benefits of the oxygen hydrogen RCS will also require development of a system to use propellants from the main propulsion tankage. Thrusters will likely require gaseous propellants for satisfactory pulsing operation. An efficient, reliable method of generating gaseous hydrogen and oxygen from the stored liquids is needed. The variable flow demands inherent in the RCS application cause the design of a stable system to be extremely difficult.

STV

REACTION CONTROL SYSTEM

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SYSTEM DESCRIPTION	ADVANTAGES	DISADVANTAGES
<ul style="list-style-type: none"> •MONOPROPELLANT HYDRAZINE •CURRENT TECHNOLOGY 	<ul style="list-style-type: none"> •SIMPLEST SYSTEM •WELL CHARACTERIZED •PRESSURANT NITROGEN STORED IN PROPELLANT TANKS 	<ul style="list-style-type: none"> •LOW PERFORMANCE •TOXIC PROPELLANTS •LIMITED THRUSTER LIFE •SEPARATE SYSTEM FOR OPERATION AT SPACE STATION
<ul style="list-style-type: none"> •BIPROPELLANT N2O4-MMH •CURRENT TECHNOLOGY 	<ul style="list-style-type: none"> •GOOD PERFORMANCE •WELL CHARACTERIZED 	<ul style="list-style-type: none"> •TOXIC PROPELLANTS •MAXIMUM NUMBER OF STATION INTERFACES •CONTAMINATING EXHAUST - MMH NITRATE
<ul style="list-style-type: none"> •OXYGEN HYDROGEN •SYSTEM INTEGRATED WITH FUEL CELLS •SUPERCRITICAL CRYOGENIC FLUID STORAGE 	<ul style="list-style-type: none"> •GOOD PERFORMANCE •NO UNIQUE FLUIDS REQUIRED •NON TOXIC •POTENTIAL TO USE THRUSTERS IN SINGLE FLUID MODE FOR OPERATION NEAR STATION 	<ul style="list-style-type: none"> •TECHNOLOGY RISK, SYSTEM DYNAMICS •THRUSTER DEVELOPMENT
<ul style="list-style-type: none"> •OXYGEN HYDROGEN •SYSTEM INTEGRATED WITH MAIN ENGINES •PROPELLANTS STORED AS LIQUIDS, PUMPED TO HIGH PRESSURE TANKS OR ACCUMULATORS 	<ul style="list-style-type: none"> •GOOD PERFORMANCE •NO UNIQUE FLUIDS REQUIRED •NON TOXIC •POTENTIAL TO USE THRUSTERS IN SINGLE FLUID MODE FOR OPERATION NEAR STATION 	<ul style="list-style-type: none"> •TECHNOLOGY RISK, SYSTEM DYNAMICS •THRUSTER DEVELOPMENT •HIGH SYSTEM RELIABILITY MAY BE DIFFICULT

ENGINE DESIGN MARGINS

Design margins for the STV engine should be higher than normally used for unmanned vehicles which have no reusability requirements. Increased design margins should provide the increased reliability and longer life needed for the human exploration program.

STV

ENGINE DESIGN MARGINS

STV Engine Design Considerations

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- DESIGN MARGINS ARE NEEDED TO:
 - ASSURE HIGH RELIABILITY
 - MAINTAIN HIGH RELIABILITY TO END OF ENGINE LIFE
- MARGINS VERIFICATION BY COMPONENT TESTS
 - VALVES CYCLE LIFE
 - THRUST CHAMBER TEMPERATURE/PRESSURE CYCLES
 - ROTATING MACHINERY
 - ROTATIONAL SPEED
 - PRESSURE/TEMPERATURE CYCLES
 - THROTTLING
 - MISSION DUTY CYCLE
- MIXTURE RATIO CONTROL CAPABILITY

ENGINE CONFIGURATION & CHARACTERISTICS

The STV engine is expected to be space based with a primary mission to support the human exploration program for several years. The STV engine will also be required to provide propulsion capability for a variety of commercial and military missions. High reliability is essential to achieve a man rated vehicle capable of efficient operation in a space based mode. Design for maintainability in space is also a major consideration in efficient operation of the propulsion system.

***STV* ENGINE CONFIGURATION & CHARACTERISTICS**

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- RELIABILITY IS A PRIMARY CONSIDERATION
 - REDUNDANT COMPONENTS WHERE FEASIBLE
 - DESIGN FOR ZERO MAINTENANCE
- ENGINE REMOVAL AND REPLACEMENT IN SPACE
 - MINIMUM NUMBER OF CONNECTORS
 - READILY ACCESSIBLE INTERFACE CONNECTORS
 - VERIFY CONNECTORS INTEGRITY WITHOUT LOSS OF FLUID
 - VERIFY ELECTRICAL SYSTEM WITHOUT HARDWARE FUNCTION
- GASEOUS OXYGEN AND HYDROGEN BLEED PRESSURIZATION
- USE HYDROGEN FOR PNEUMATIC POWER IF NEEDED
- PERFORMANCE AND CONTROLS
 - THROTTLE FROM 10% TO 100% THRUST
 - WIDE RANGE OF MIXTURE RATIO CONTROL

GENERAL DYNAMICS
Space Systems Division

**UPPER STAGE
PROPULSION
TECHNOLOGY REQUIREMENTS**

Hal Hahn

PROPULSION SYSTEM DESIRED FEATURES
Improve Launch Processing, Performance, Cost, Reliability, Safety

- **Simplified Subsystems**
 - Single Engine
 - No Active Thrust Control
 - No Propellant Utilization
 - No Prelaunch Chilldown
 - Low NPSP, Simplified Pressurization
 - Simplified Environmental Control (No Purges)
 - Electromechanical Valve Controls
 - EMA TVC
 - All Welded System
 - Redundant Seals at Seperable Connections (i.e. lipseals)
 - Integral Heat Exchangers for Warming Pressurant Gas or
 - Autogenous H2 and O2 Pressurization Systems
- **Enhanced Checkout, System Monitoring**
 - IHM - Integrated Health Monitoring
 - BIT - Built in Test
 - Automatic Operations, Checkout
- **Minimal/No Catastrophic Failure Modes**
- **Robust Margins**
- **Fault Tolerance**

BENEFITS OF SINGLE ENGINE CENTAUR/UPPER STAGE

- | | |
|--|---|
| Increases Payload Capability: | <ul style="list-style-type: none">• A/C 415 lbs to GTO• T/C 1100 lbs to GEO |
| Reduces Cost: | <ul style="list-style-type: none">• Save 1/2 Main Propulsion Hardware |
| Increases Reliability | <ul style="list-style-type: none">• Reduces Number of Parts |
| Reduces Launch Processing Time and Cost | <ul style="list-style-type: none">• Reduced Amount of Hardware to Checkout• Simplifies Propulsion System |

INCREASED THRUST AND SPECIFIC IMPULSE NEEDED

- Today; RL10A-4 Engine on Atlas/Centaur has
20.8K lbf thrust (each of 2 engines)
450 sec isp
- Single Engine Centaur on Atlas Requires
35K lbf thrust
Maximum possible specific impulse
- Advanced Upper Stage for HLV Requires
> 50K lbf thrust

UPRATED RL10 ENGINE VS NEW ENGINE

RL10 Derivative
35K lb Thrust, FSD

1990 1995 2000

Advanced Engine
Test Bed (20K)
FSD

Near Term Needs
35K lbs Thrust

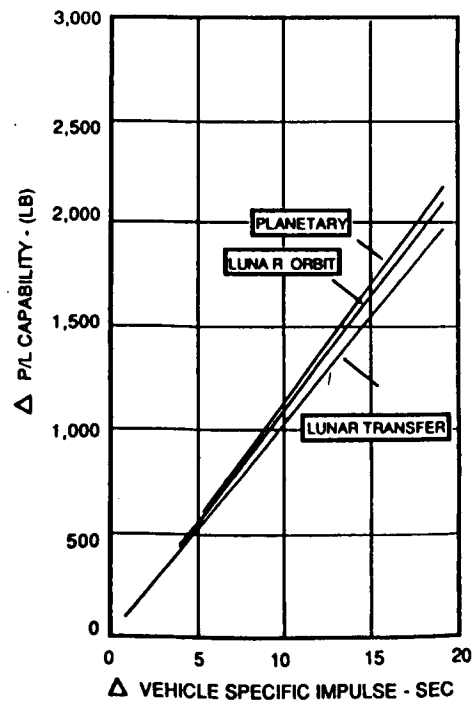
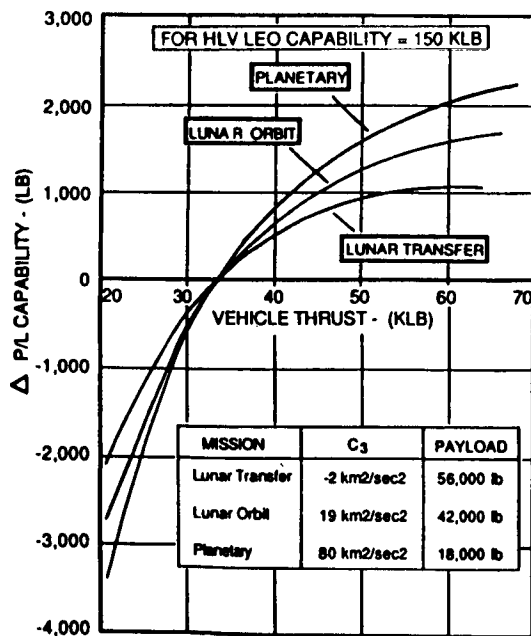
- Develop RL10 to Full Capability or 5 Year Time Table
- Only the RL10 Will Satisfy Near Term Needs
- Single Engine A/C ELV

Intermediate to Longer Term

- > 50K lbs Thrust — Use Two 35K RL10s
- Accelerate FSD of Advanced Engine (Size for > 50K Instead of 20K)

Upgraded Centaur Study

THRUST AND SPECIFIC IMPULSE EFFECT ON PERFORMANCE CAPABILITY



ATLAS IIAS - SINGLE ENGINE CENTAUR STUDY THRUST AND SPECIFIC IMPULSE SENSITIVITIES

